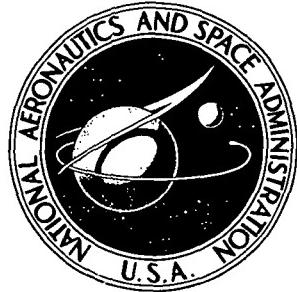


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DESIGN, PERFORMANCE, AND EVALUATION
OF A DIRECT-CURRENT CONTACTOR
FOR SPACE NUCLEAR ELECTRICAL SYSTEMS

by Lawrence A. Mueller, David W. Medwid,
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SUMMARY

A direct-current contactor for use in large space power systems was designed, built, and tested. It was developed to be operational in an environment of 540°C (1000°F) and at a pressure of 10^{-4} N/m^2 (10^{-6} torr) or lower. The contactor is rated to pass 10 amperes continuously and to interrupt a 20-ampere current at 10 000 volts.

The contactor was tested to determine the corona threshold level and the leakage current at several temperatures and pressures. At 540°C (1000°F) and a pressure of 10^{-5} N/m^2 (10^{-7} torr) the corona level at its rating of 10 000 volts was 3.0 picocoulombs and the leakage current was 1.3 milliamperes. At 20 000 volts the corona was 6.6 picocoulombs and the leakage current was 5.2 milliamperes. This gives the contactor a 100-percent safety factor, which can be utilized to handle any transient voltage spikes up to 20 kilovolts.

The contactor was also tested for its closing and interruption ability. It successfully interrupted currents up to 23 amperes at 12.5 kilovolts.

INTRODUCTION

Future large spacecraft systems with 500- to 1000-kilowatt-electric power supplies will require high-capacity circuit breakers and contactors. Vacuum interrupter switching devices for application in conventional power, utility, industrial, and radio transmitter switching systems have been used extensively for a number of years. They have proven to be very satisfactory devices, providing fast, reliable interrupting characteristics. Such vacuum devices are not suitable, however, for nuclear space power electrical systems which operate at temperatures as high as 540°C (1000°F) and in a space

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vacuum environment. The materials used are incapable of withstanding the high ambient temperatures; and typical actuating mechanisms of existing vacuum switches, which include rolling or sliding surfaces, would seize or weld in the long-term space vacuum environment.

This report describes the design and testing of a direct-current contactor rated at 10 000 volts and 10 amperes for operation in an environment of 540°C (1000°F) and a vacuum of 10^{-4} N/m^2 (10^{-6} torr) and lower. The contactor design is similar to a 1000-volt, 600-ampere, 1000-hertz circuit breaker described in reference 1. The rating of the contactor is such that it could be used for ion engine protection and switching.

Corona tests were conducted to determine the corona threshold voltage and the voltage withstand of the contactor. Also evaluated was the effect of temperatures to 540°C (1000°F) and pressures of 10^{-4} N/m^2 (10^{-6} torr) and lower on the corona threshold voltage.

Switching tests were also conducted as reported in the appendix. They include "close-open" interruption tests and also "open only" tests. The switching tests were performed with an early design of the contactor. The contactor was subsequently modified to improve its corona characteristics. All corona and leakage current tests were made with the improved final design. The final design differed from the earlier design in the interrupter area only. The actuating mechanisms are identical in both designs.

DESCRIPTION OF CONTACTOR

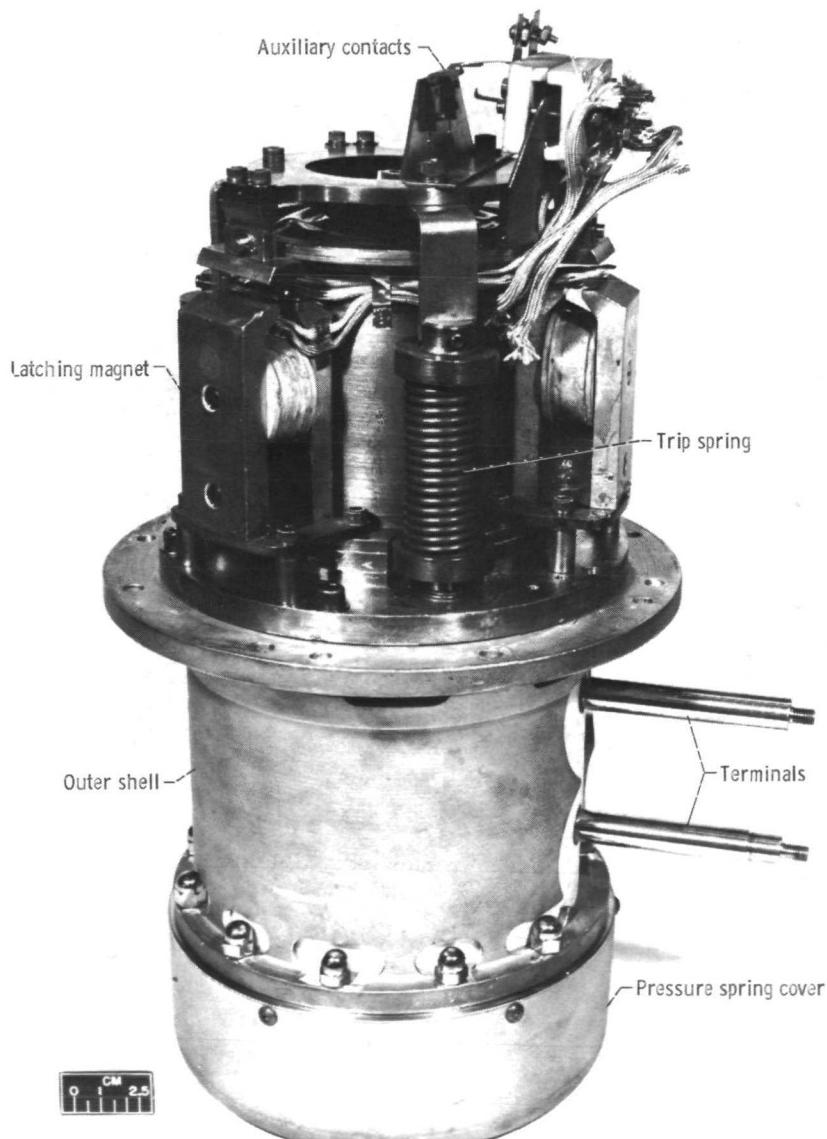
The contactor as used for the corona tests (figs. 1(a) and (b)) can be considered as being composed of six main sections:

- (1) Contacts and shield
- (2) Current-carrying flexible conductor assembly
- (3) Outer shell, insulators, and terminals
- (4) Wipe-spring subassembly
- (5) Pressure springs and cover
- (6) Actuating mechanism

Contacts and Shield

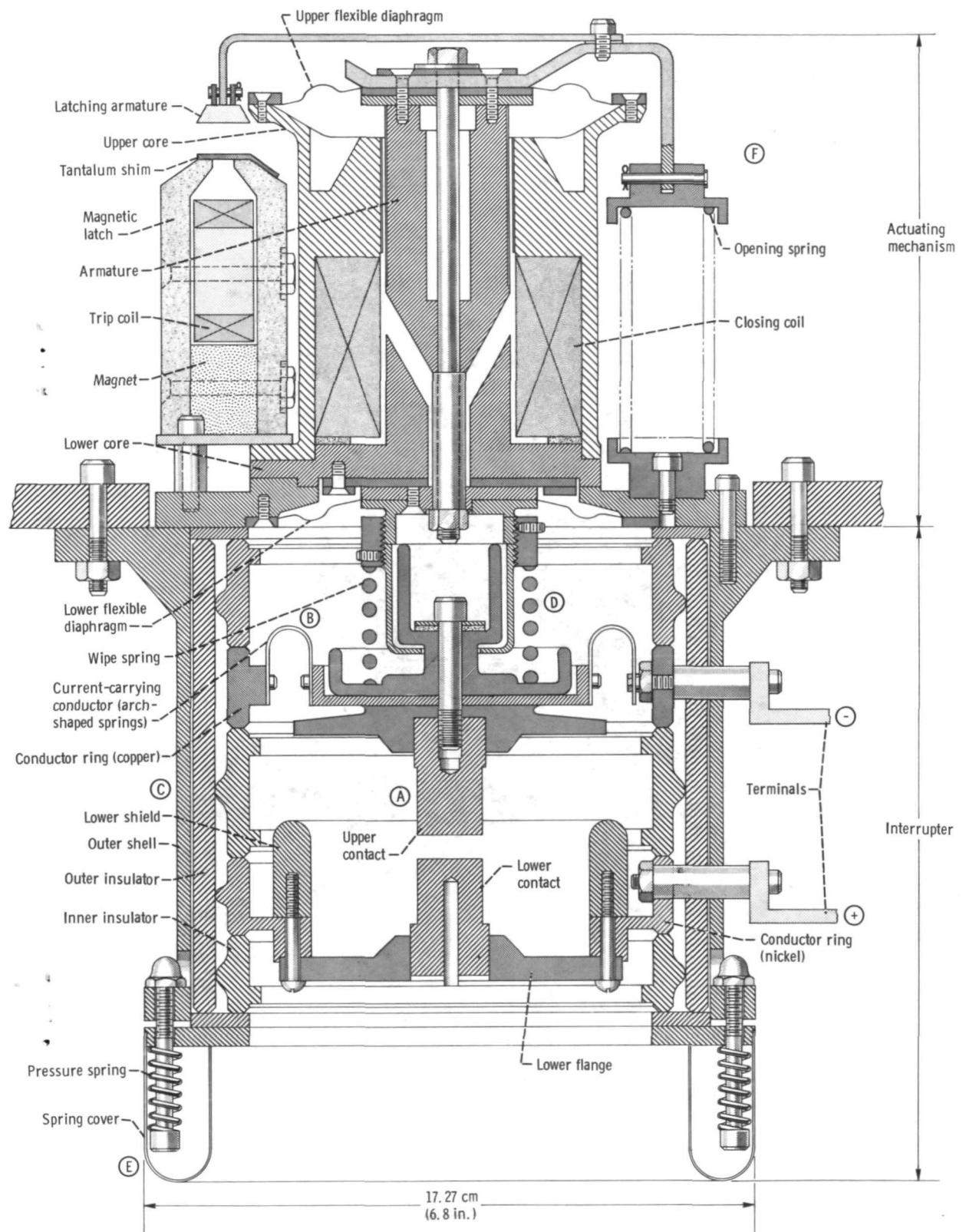
The interrupter contains the two molybdenum contacts which open and close the circuit (fig. 1(b), section A). They were made from arc-cast, vacuum-melted molybdenum and are 1.9 centimeters (0.75 in.) in diameter. They are brazed to Amzirc (Cu-0.15Zr) flanges. Amzirc has high strength ($21\ 500\text{ N/cm}^2$, or 31 100 psi) at a temperature of 500°C (930°F) and also has low electrical resistivity (6.1 ohm-cm).

A stainless-steel shield is installed around the lower contact. The surface is polished all around. It has a twofold purpose. Besides being an arc spatter shield during an interruption or closing operation of the contactor, it also shielded the sharp edges (a source of electron emission) of the round-head screws and nuts that fastened the lower Amzirc flange to the nickel conducting ring.



(a) Complete assembly with mechanism.

Figure 1. - Direct-current contactor.



(b) Cross section.

Figure 1. - Concluded.

Current-Carrying Flexible Conductor Assembly

The current-carrying flexible conductor assembly (fig. 1(b), section B) is composed of an oxygen-free high-conductivity copper ring and plate with Cube alloy arch-shaped springs 0.015 centimeter (0.006 in.) thick and 1.27 centimeters (0.5 in.) wide. Cube alloy (Cu-0.5BeO) consists of fine particles of beryllia dispersed in a copper matrix in order to strengthen the copper and to prevent recrystallization and grain growth (ref. 2). Its tensile strength at 540° C (1000° F) is $31\,000\text{ N/cm}^2$ (45 000 psi).

A flexible conductor assembly was successfully tested at 650° C (1200° F) for 1000 hours in a vacuum of 10^{-4} N/m^2 (10^{-6} torr). During this test, the assembly was mechanically flexed 1000 times, simulating 1000 operations (ref. 3).

Outer Shell, Insulators, and Terminals

The outer shell is nickel, and the cylindrical ceramic insulators are 99.8-percent alumina (fig. 1(b), section C; and fig. 2). The 1.9-centimeter (0.75-in.) holes in the insulating rings are for venting the area between the two concentric insulating liners. The upper and lower faces of the ceramic insulators are metallized with molybdenum manganese to provide good contact with the metal conducting rings and also to seal off the microscopic voids in the surface.

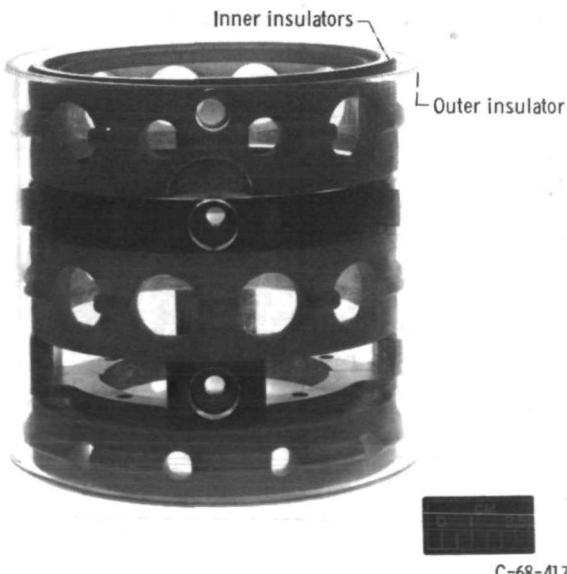


Figure 2. - Model of inner ceramic insulators. Note annular clearance.

The positive and negative terminals are Cube alloy. A high-strength copper was required for these parts since they are bolted to the conducting rings. Ordinary oxygen-free high-conductivity copper anneals at the operating temperature, and the connection would loosen and cause high resistance at the junction.

Wipe-Spring Subassembly

The wipe-spring subassembly (fig. 1(b), section D) is composed of an alumina cup and a split nickel cup with a nickel washer and nut. Also, a Mica-mat split washer is used between the ceramic cup and the split nickel cup. Mica-mat is an inorganic, bonded, rigid mica plate. It serves as a damper during the opening operation. The nut is used to adjust the preload of the Inconel 718 wipe spring. When the closing mechanism (see fig. 1(b)) moves the upper contact 0.63 centimeter (0.25 in.) downward and it mates with the lower contact, an initial force of 88 newtons (20 lbf) from the preloaded wipe spring is produced between the faces of the contacts. The mechanism is so designed that it continues to move an additional 0.31 centimeter (0.12 in.) after the contacts have initially mated, and an additional force of 35 newtons (8 lbf) is produced on the contacts for a total of 123 newtons (28 lbf). This pressure loading on the electrode faces ensures the required electrical contact.

Pressure Springs and Cover

Eleven pressure springs were used to provide pressure on the cylindrical ceramic insulators and the metal conducting rings (fig. 1(b), section E). This pressure is required to keep the assembly tight at the 540° C (1000° F) operating temperature. Since the outer nickel shell of the interrupter section grows thermally more than the inside alumina cylinders and metal conducting rings, a gap would develop between the dielectric and the metal surfaces. This looseness or gap at the interfaces causes high voltage gradients and can be a source of corona and high leakage current.

The springs are made from Inconel X750. For long-time use, springs made from one of the higher strength superalloys (possibly Inconel 718) would be required. At room temperature, the 11 springs provide 580 newtons (132 lbf) on the assembly. This keeps all the interfaces tight at temperatures up to 540° C (1000° F).

The smooth-surface stainless-steel cover was required to shield any sharp edges of the springs.

Actuating Mechanism

The actuating mechanism (fig. 1(b), section F) consists of a closing solenoid, three flux-shift latching magnets with trip coils, and three trip springs. In addition, a set of auxiliary contacts are mounted on top (fig. 1) to indicate the position of the contactor mechanism during operational testing.

The closing solenoid consists of the coil, the armature or plunger, the upper core, and the lower core. The solenoid was designed to provide a minimum force of 444 newtons (100 lbf). The solenoid force must compress the wipe-spring assembly (123 N, or 28 lbf) plus the three trip springs (119 N, or 27 lbf) for a total of 242 newtons (55 lbf) during the closing operation.

The three flux-shift latching magnets hold the mechanism in the closed position when the closing solenoid is activated. They are arranged around the mechanism's central core (with its closing coil and armature) between the three opening springs. The latch armatures are attached to a three-pronged plate mounted to the top moving assembly.

In operation, when the armature is closed, the flux path is from the magnet, through the side pieces, across the short gaps, and through the armature, providing a strong armature holding force. When the trip coil is energized, the resulting magnetomotive force overcomes the large gap reluctance. The flux then follows the large gap reluctance and takes the new and shorter path through the annulus of the trip coil. This decreases the armature holding flux by 95 percent or more, so the armature is released from the closed position. Release time is as short as 3 milliseconds. With the mechanism mounted on the interrupter section, the effective opening time of the contactor is 8 to 10 milliseconds.

The three trip springs (fig. 1) are helical springs made from Inconel 718. When the mechanism is in the closed position, the trip springs are under a load of 40 newtons (9 lbf) each. When the trip coils in the latching magnet assemblies are activated, the three trip springs (in conjunction with the wipe spring) release the mechanism from the closed position and the contacts are parted.

The auxiliary contacts were incorporated to indicate the position of the contactor mechanism; this is essential for proper and full recording of the operation. The moving contacts are attached to the moving top plate of the actuating mechanism. A small battery and resistor are connected between ground and each insulated contact and in series with a galvanometer on the visicorder. When the contacts close, the galvanometer is deflected. The adjustment is such that one contact is closed at the full-open position of the mechanism, and the other at the full-closed position.

The mechanism is identical to that used on the alternating-current breaker (ref. 1). It was operated over 200 times with excellent results at 540°C (1000°F) and at pressures of 10^{-4} N/m^2 (10^{-6} torr) and lower. Also, it is described in more detail in reference 1.

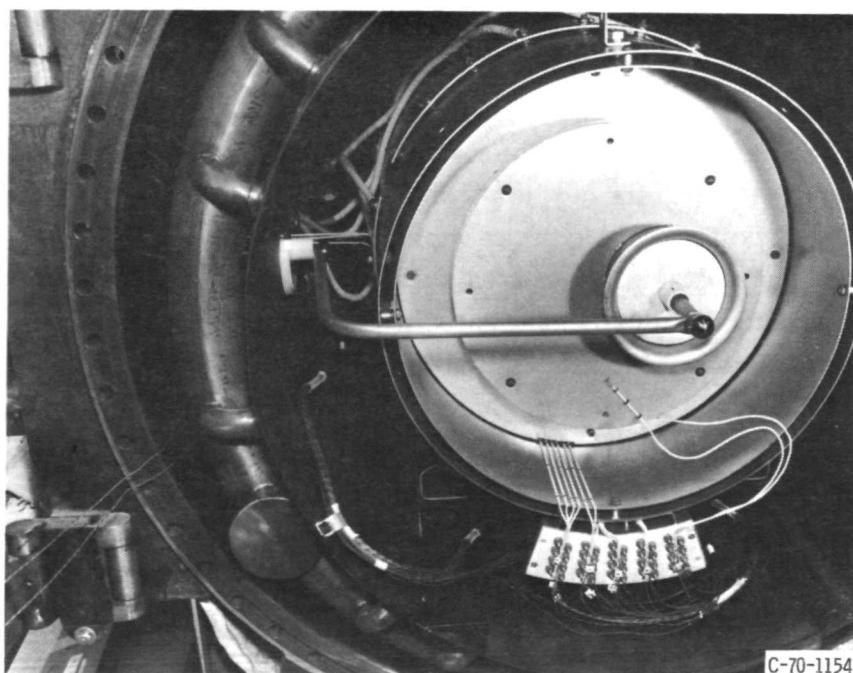
APPARATUS AND PROCEDURE

Apparatus

Corona oven. - An oven of special design (fig. 3) had to be built to fit the vacuum chamber and also to accommodate the test piece. It has a temperature range to 815°C (1500°F). The nominal dimensions are as follows: diameter, 51.3 centimeters (20.2 in.); and length, 98.3 centimeters (38.7 in.). Twenty-four quartz lamps are equally spaced around the circumference. They are wired up in three banks of eight lamps each. This provides flexibility to ensure uniform heating of the test piece. In case a lamp would fail during the test, the voltage on that particular bank could be increased.

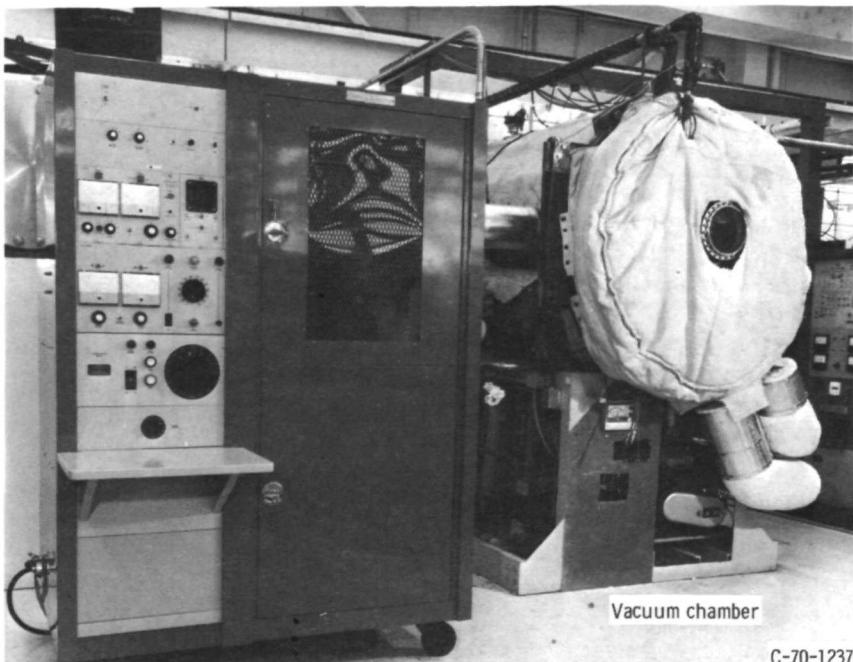
The oven material is type 304 stainless steel. Alumina and boron nitride are used at insulating points. Two vacuum gages are mounted on the end baffle of the oven to monitor the pressure as close as possible to the test piece. Eighteen thermocouples are installed on the oven at discrete points to monitor the temperatures.

Vacuum chamber. - The vacuum chamber used in the corona test has a 10^{-6}-N/m^2 (10^{-8}-torr) range. It is equipped with a liquid-nitrogen cold baffle, heaters, and four vacuum pumps: a roughing pump, a turbomolecular pump, an ion pump, and a titanium sublimation pump. The cold baffle is used as a heat sink and for cryogenic pumping.



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Figure 3. - Oven inside vacuum chamber, showing high-voltage lead with corona balls.



* Vacuum chamber

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Figure 4. - Corona test set.

The heaters provide for specimen bakeout. The nominal dimensions are as follows: diameter, 101 centimeters (40 in.); and length, 183 centimeters (72 in.).

Corona test set. - The corona test set (fig. 4) is a nondestructive testing apparatus used for detecting the corona threshold level of electrical devices. The voltage range of the set used in the tests is 40 kilovolts dc and 25 kilovolts ac.

Procedure

For the corona tests, only the lower half of the assembly (interrupter section) was used. This section includes all parts which are at high voltage in normal operation. The mechanism which moves the movable contact is not included since we are concerned with the static condition of open contacts having a gap of 0.95 centimeter (0.37 in.). An adjustable screw clamp provides the support and adjustment for the movable contact.

The test piece is mounted in a horizontal position in the oven (fig. 5) installed inside the vacuum chamber. The high voltage is brought in from the corona test set through a bushing and lead which are designed to be corona free. The plus dc voltage was connected to the lower (fixed) contact. The upper (movable) contact and the outer nickel shell were grounded. The power for the quartz lamps to provide the heat is controlled by setting of the controller, and the input rate is regulated by adjustment of the voltage applied. Pressure is controlled by manipulation of the vacuum pumps.

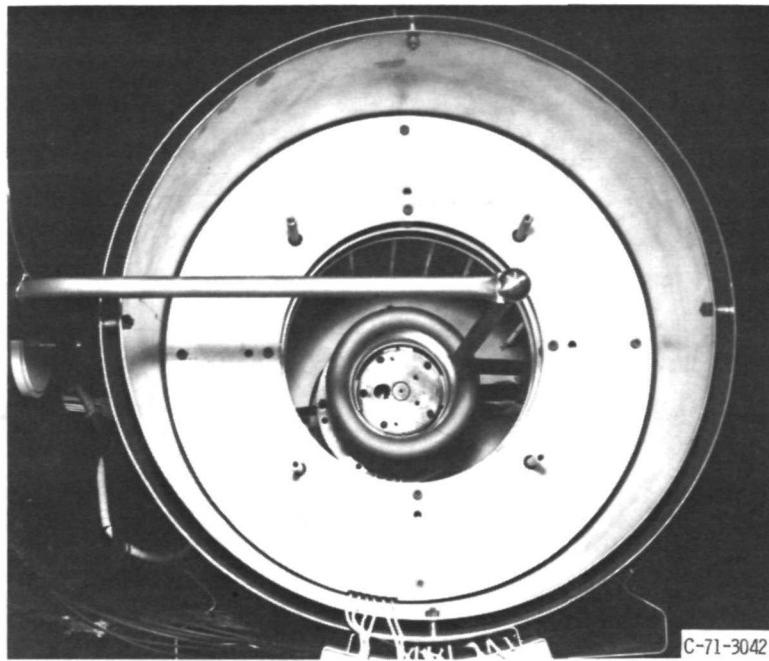


Figure 5. - Interrupter section of contactor installed in oven, showing high-voltage lead connected to lower contact.

The testing procedure used can be summarized as follows:

(1) The entire system, including the corona test set, was checked out with the contactor out of the oven by baking out the system and determining if corona was present. The temperature was run to 540° C - (1000° F) , the same as for the later testing, to assure performance of the oven and other parts at this temperature.

(2) The contactor was installed and the lower terminal (positive) was connected to the high-voltage lead, while the other terminal (upper contact) and case were grounded. The system was evacuated and baked out to get the contactor into proper operating condition.

(3) The effects of temperature on corona threshold voltage were then determined by holding the chamber vacuum at constant pressure while the temperature varied from 20° to 540° C (68° to 1000° F) in discrete steps.

(4) The following data were recorded for each test point:

- Leakage current at 1000 volts dc to determine the insulation resistance
- Corona threshold voltage and leakage current for positive test voltage
- Chamber pressure
- Contactor temperature

(5) Voltage was increased in 2.0-kilovolt steps until 20 kilovolts was reached (twice the rating of the contactor). Corona readings in picocoulombs and leakage current were recorded. The pressure in the chamber during the runs was in the 10^{-5}-N/m^2 (10^{-7} -torr) to 10^{-6}-N/m^2 (10^{-8} -torr) range.

RESULTS AND DISCUSSION

Measurement of corona level and leakage current gave the following results for a pressure of 10^{-5} N/m² (10^{-7} torr):

Temperature		Voltage			
°C	°F	10 kV	20 kV	10 kV	20 kV
Corona level, picocoulomb			Leakage current, mA		
315	600	(a)	(a)	(a)	(a)
430	800	1.0	10.0	0.003	0.032
540	1000	3.0	6.6	1.3	5.2

^aNegligible.

The value of corona level is acceptable up to 20 kilovolts (twice its rated voltage) at 540° C (1000° F). The value of the leakage current at 10 kilovolts is acceptable, but at 20 kilovolts it is somewhat high. Since the contactor was designed for 10 kilovolts, it amply meets the specification. Since the level of corona at 20 kilovolts is very low, this gives the contactor a 100-percent safety factor (when operating at 10 kilovolts) to handle any transient voltage spikes up to 20 kilovolts even at 540° C (1000° F).

If the operating temperature were reduced to 430° C (800° F), the contactor could operate at twice its rating (20 kV) since the leakage current was very low (0.032 mA) at this temperature.

The slight increase in both corona and leakage current with the increase in temperature can be attributed largely to both the reduction in tension produced by the Inconel X750 pressure springs at the elevated temperatures and the decrease in resistivity of the alumina insulators (ref. 4). Another possible contributing factor is an increase in the outgassing of the materials at the higher temperatures.

During the course of the test, an arc-over occurred across the open contacts at 19 kilovolts and 95° C (200° F). Also, at 205° C (400° F) arc-over occurred at 19 and 20 kilovolts. Reference 5 notes that if the electrode gap is continually sparking over, even in vacuum only, the breakdown voltage increases until it reaches a plateau. Evidently, this was conditioning of the contacts since it never occurred after that, even at the much higher temperature. Slivkov (ref. 6) found that for heated nickel electrodes at temperatures up to 800° C (1470° F) the breakdown strength coincided within 5 percent with those measurements obtained at ambient temperature. Since no arc-over occurred at the 540° C (1000° F) test temperature, it appears that breakdown voltage is not significantly influenced by temperature.

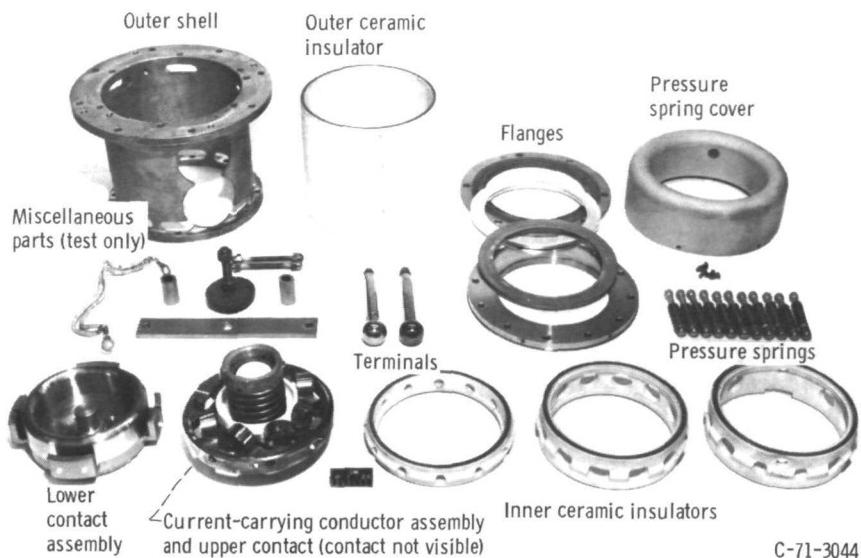


Figure 6. - Contactor disassembled after testing.

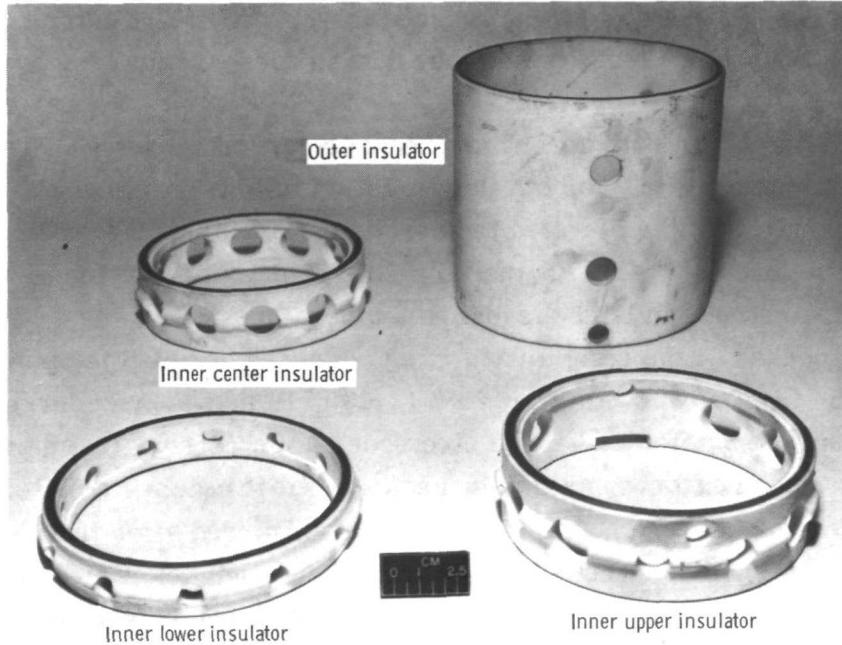


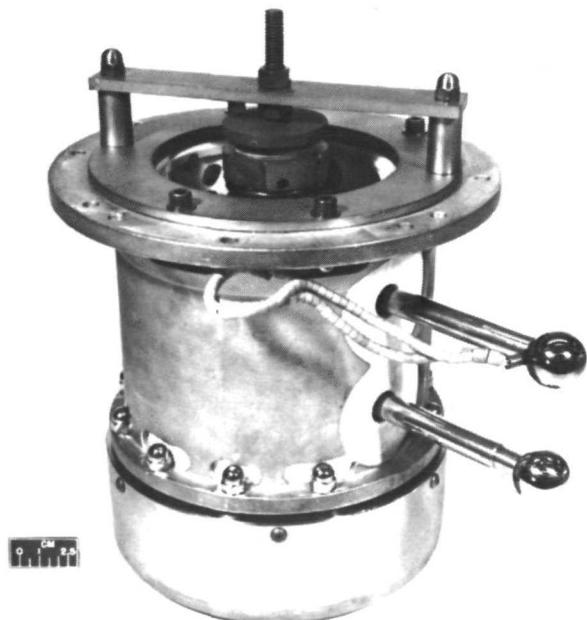
Figure 7. - Ceramic insulators after testing.

Differences of pressure in the 10^{-4} -N/m² (10^{-6} -torr) range and lower did not appear to be a factor in the corona level.

The contactor was also tested with reversed polarity. The significant increase in corona that resulted suggests that the contactor would have to be derated to be used with reverse polarity. Therefore, for maximum service life the contactor should be hooked up with the plus dc voltage applied to the lower (fixed) contact and the upper (movable) contact grounded.

Upon completion of all the tests the contactor was disassembled and inspected (figs. 6 and 7). Minor deterioration of components was observed:

(1) The ceramic insulators did show some contamination. One of the heavier areas coated (metallic) was on the outer insulator where the terminals penetrate the shell (area that appears as a figure eight in fig. 8). The upper inner insulator (fig. 7) had one spot that was discolored. The inner set of ceramic insulators were in good shape.

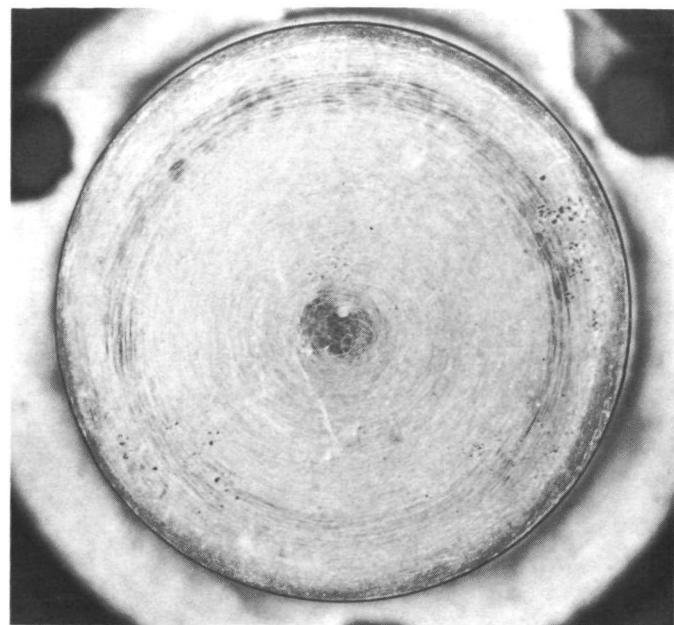


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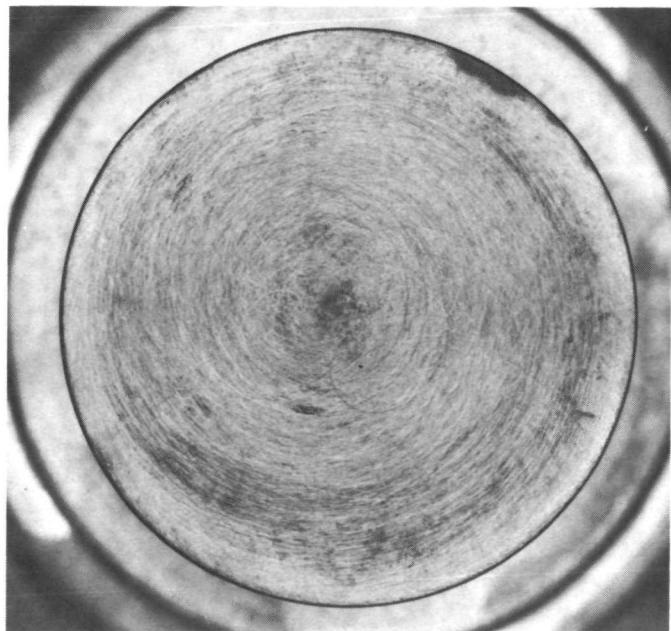
Figure 8. - Interrupter section after testing at 540° C (1000° F).

(2) A few small pit marks were evident on the contacts (fig. 9). These are presumed to have resulted from the operational tests described in the appendix. They had been exposed to 25 amperes inrush current during the tests.

(3) The Amzirc flange supporting the lower contact was slightly deflected. This also happened during the operational tests in the closing and opening tests of the contactor.



(a) Upper contact.



(b) Lower contact.

Figure 9. - Contact surfaces of direct-current contactor after testing. X4.

Based on these results, it may be concluded that the contactor design is satisfactory and meets its design specifications. However, the results do suggest some possible improvements.

The improvements that can be made to the existing contactor without a complete redesign are the following:

(1) An alumina upper shield could be added, as shown in figure 10. During closing and opening operations of the contactor this shield would overlap the lower shield and intercept the spatter from the contacts. This shield should be spaced at least 1.27 centimeters (0.5 in.) from the upper contact and also the same distance from the lower shield.

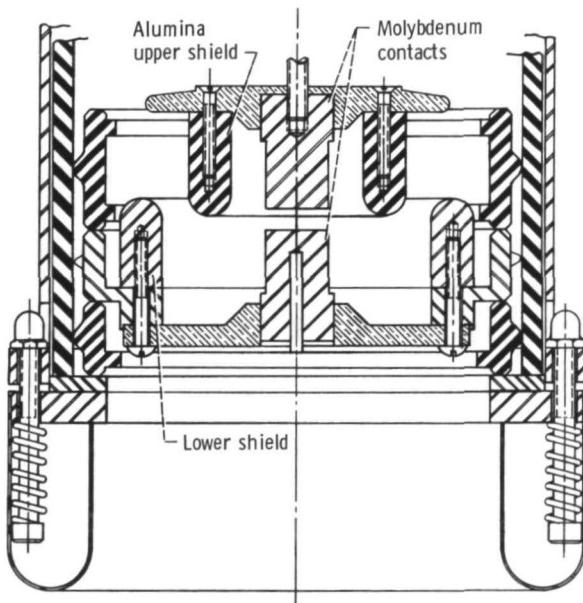


Figure 10. - Interrupter shown with semi-torus-shaped shields.

(2) The material of the pressure springs could be changed to give more tension at the 540°C (1000°F) operating temperature. This could be done by using one of the super-alloys, such as L-605 or René 41. Also Inconel 718 may be satisfactory. If the springs are at room temperature, the pressure on the interfaces of the insulators and metal conducting rings of the assembly was 47 N/cm^2 (69 psi) from the 11 springs. This should be increased to approximately 69 N/cm^2 (100 psi). This allows for the normal decrease in torsional modulus of the material at the 540°C (1000°F) operating temperature.

(3) A toroidal ring could be added around the opening in the outer nickel shell where the terminals penetrate. This is particularly required for the positive terminal since the present cutout of the shell has sharp edges. The torus would provide a smooth radius edge and eliminate any possibility of corona discharge taking place between the positive

terminal and the shell (which is grounded) and contaminating the surface of the outer ceramic insulator.

(4) A radius edge could be provided on the face of the contacts. A 0.63-centimeter (0.25-in.) radius would be desirable. This would leave a 0.63-centimeter (0.25-in.) diameter flat spot in the center for the current-conducting surface in the closed operation of the contactor, which is ample for the 10-ampere rating.

The original contactor design called for a 0.63-centimeter (0.25-in.) spacing of the contacts, but this was changed to 0.95 centimeter (0.375 in.) for the tests. Tests of the spacing required for the contacts under ambient pressure and temperature conditions showed that for flat-face contacts with 0.04 centimeter (0.015 in.) by 45° chamfered edges, spaced 0.71 centimeter (0.28 in.) apart, a voltage of 19.5 kilovolts could be reached before arc-over would occur. For a 1.0-centimeter (0.40-in.) spacing, a voltage of 24 kilovolts could be reached. Arc-over would occur from chamfered edge to chamfered edge of the contacts.

For radius edge contacts with a 0.63-centimeter (0.25-in.) flat spot in the center and an edge radius of 0.63 centimeter (0.25 in.) under the same conditions, arc-over occurred at 21 kilovolts for a spacing of 0.71 centimeter (0.28 in.). And for a spacing of 1.0 centimeter (0.40 in.), arc-over did not occur until 29.3 kilovolts was reached. Therefore, it is recommended to have a radius on both contacts.

(5) A stainless-steel plate or flange could be used to back up the Amzirc flange that supports the lower contact. Another method that could possibly be used would be to make the current conducting plate out of Cube alloy (a much stronger copper at the 540° C (1000° F) operating temperature).

(6) The outer copper conducting ring of the flexible current conductor assembly could be positioned 0.47 centimeter (0.187 in.) lower than the inner plate (one-half of its total deflection) when the contactor is in the open position. This would put the arch-shaped springs under a negative stress in the open position of the contactor. Then, upon closing of the contacts, the inner plate moves downward 0.95 centimeter (0.375 in.) and the stress goes to a positive value. This half travel (or deflection) of the arch-shaped springs (from their neutral point) from a negative deflection to a positive value reduces the stress to one-half.

Since the solenoid section of the mechanism was originally designed to move downward 0.95 centimeter (0.375 in.) for the 0.63-centimeter (0.25-in.) spacing of the contacts, it will now have to be increased by 0.32 centimeter (0.125 in.) since the tests were conducted with the contacts spaced 0.95 centimeter (0.375 in.) apart.

Another improvement that could be made but would require increasing the diameter of the contactor by 7.0 to 8.0 centimeters (2.7 to 3.1 in.) would be the incorporation of the contacts in a vacuum capsule as in the original design. This requirement is only necessary if a full-scale test of the complete power system at its operating temperature would be required on the launch pad. If the full-scale test is not required, the contactor

could be checked on the launch pad with a low voltage to ensure its operational ability without using a sealed capsule. For space operation the vacuum capsule is not required.

The reason for the increase in the diameter of the contactor is that it was found during testing that all shields around the contacts must have a large radius at the ends, good results being obtained with a radius of approximately 0.6 centimeter (0.24 in.). The sharp edges of the original shields inside the capsule were the source of glow discharge and arcing.

CONCLUDING REMARKS

A direct-current contactor (10 kV, 10 A) was built for operation at 540° C (1000° F) and at a pressure of 10^{-4} N/m² (10^{-6} torr) or lower. The contactor was tested at 10 kilovolts with a 100-percent margin on voltage in order to show tolerance of transient voltage spikes up to 20 kilovolts. When the operating temperature was reduced to 430° C (800° F), the contactor operated successfully at twice its rating, or 20 kilovolts.

The design features that resulted in the successful operation were the following:

(1) Maximum venting of the inner and outer ceramic insulators was provided. This was accomplished by using generous size holes in all three inner insulators and also by allowing ample spacing between the inner and outer insulators.

(2) Molybdenum-manganese metallizing was used on the interface surfaces of all the ceramic insulators. This provided maximum contact between the dielectric and the metallic conducting rings, eliminating the possibility of any high-voltage gradients in these areas.

(3) Pressure springs on the assembly kept tight all the interfaces between the ceramic insulators and the metal conducting rings at the operating temperature.

(4) All parts that are at a positive potential have round and smooth edges or surfaces. Radii of approximately 0.6 centimeter (0.24 in.) were used.

(5) A fast actuating mechanism that could operate at the high temperatures was achieved through use of selected materials for the closing and trip coils, the magnets, the armature, and the springs.

(6) For maximum service life, the contactor had the plus dc voltage connected to the lower (fixed) contact and the upper (movable) contact grounded.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 11, 1971,
112-27.

APPENDIX - OPERATIONAL TESTING OF DIRECT-CURRENT CONTACTOR

The contactor, complete with mechanism (fig. 11), was energized for close-open operations and interruption tests in its original configuration. The original configuration, shown in figure 11, differed from the final as follows:

(1) The contacts were enclosed in a vacuum capsule that had a tube protruding from the lower flange that could be connected to a vacuum source. The purpose of this was to be able to operate the contactor on the launch pad under ambient conditions at its operating temperature of 540° C (1000° F). Operational and preliminary corona tests of the contactor were conducted with the contacts in the enclosed capsule. Since the corona threshold level was not as high as desired, it was decided to eliminate the enclosure section.

(2) The inner and outer insulators were straight cylinders (without vent holes) and, being adjacent to one another, lacked the proper outgassing capability. Some breakdown across the insulators occurred several times during the testing.

(3) The pressure springs were not in place during these tests; they were added in the modification of the contactor.

(4) In place of the arch-shaped springs for the flexible conductor assembly, a thin copper diaphragm was used.

Object of the test was to subject the contactor to opening operations to check interrupting ability. The design goal of the contactor is 10 000 volts, 10 amperes (continuous) and 20 amperes interruption.

An event recorder with a time scale was used to measure the following data: voltage across the contacts, current through the contacts, close-coil current, and trip-coil current.

The power for the 10-kilovolt, 20-ampere interruption tests was obtained from a series-parallel bank of six 6-kilovolt high Q capacitors. The close and open (trip) coils were supplied from additional low-voltage capacitor banks.

The entire test sequence, including opening and closing the contacts and recording the test data, was automated. An operator was required only to initiate the test sequence.

A closeup of the contactor mounted on a copper heat sink is shown in figure 12. The heat sink has a stainless-steel tube brazed to the top surface for circulating air and to maintain the heat sink at 540° C (1000° F). Power leads being energized up to 12 kilovolts above ground during testing are insulated with high-purity alumina tubing. Thermocouples are attached at various critical temperature points.

A series of close-open interruption tests were made with an initial voltage on the capacitors up to 13.5 kilovolts. The contactor was at 540° C (1000° F) in ultra-high vacuum. A number of interruptions at the desired voltage were successfully made. Current at interruption ranged from 9.0 amperes to 23.0 amperes. During some of the tests, difficulty was experienced in reaching and holding the capacitor bank at the highest voltages

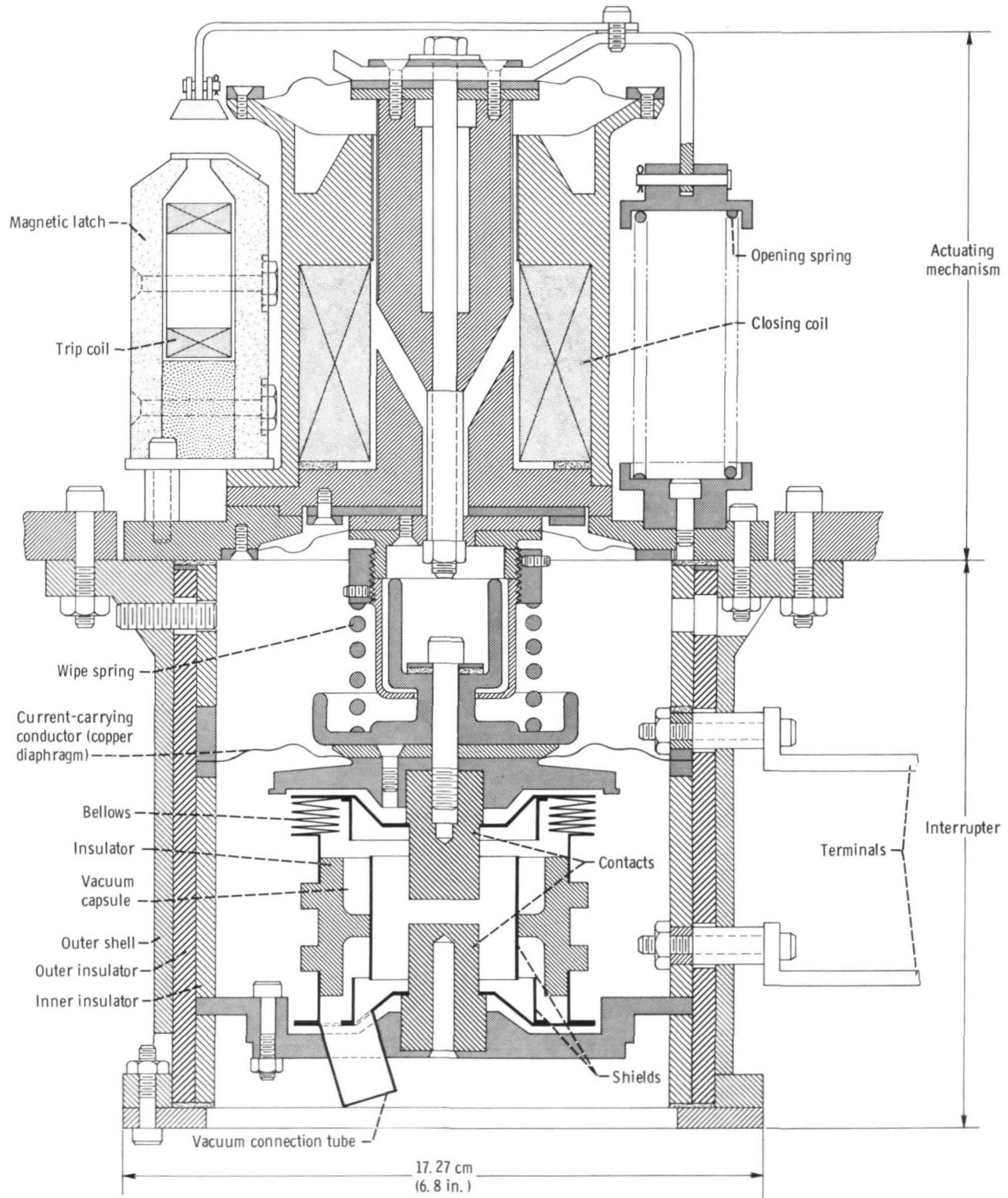


Figure 11. - Cross section of direct-current contactor with copper diaphragm conductor.

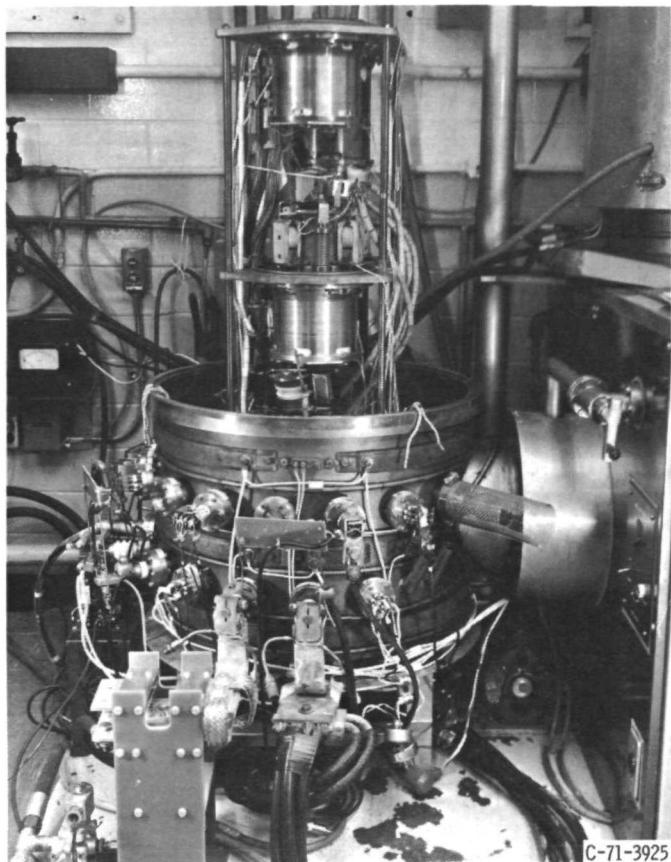


Figure 12. - Direct-current contactor set up for operational tests in vacuum tank, with thermocouples and power leads attached.

due to random and spasmadic discharges inside the vacuum tank (apparently over the contactor insulation) which would reduce the voltage suddenly by 2 to 5 kilovolts.

Meggar resistance data obtained on the contactor were as follows:

First test - room temperature: 500 megohms at 500 V

First test - 540° C (1000° F): 5.8 megohms at 500 V

After interruption tests - 540° C (1000° F): 30.0 megohms at 500 V

Final check - room temperature: infinity at 500 V

The data indicate that the interruption tests served to condition the contactor. Resistance at 540° C (1000° F) increased to five times its original value.

Contact resistance measurements were made with 10 amperes dc flowing through the contacts. Before the tests the millivolt drop was 71.0 millivolts. After the tests it measured 33.0 millivolts. This shows the contacts improved (resistance went lower).

Interruption tests were made initially with the straight "opening" control arrangement. First tests were at 2.5 and 5 kilovolts and then the initial voltage was raised to 12 kilovolts so the voltage across contacts at interruption was 10 kilovolts or higher. A total of eight tests at or above 10 kilovolts were successfully made with some time delays between tests to allow vacuum in the test tank to stabilize.

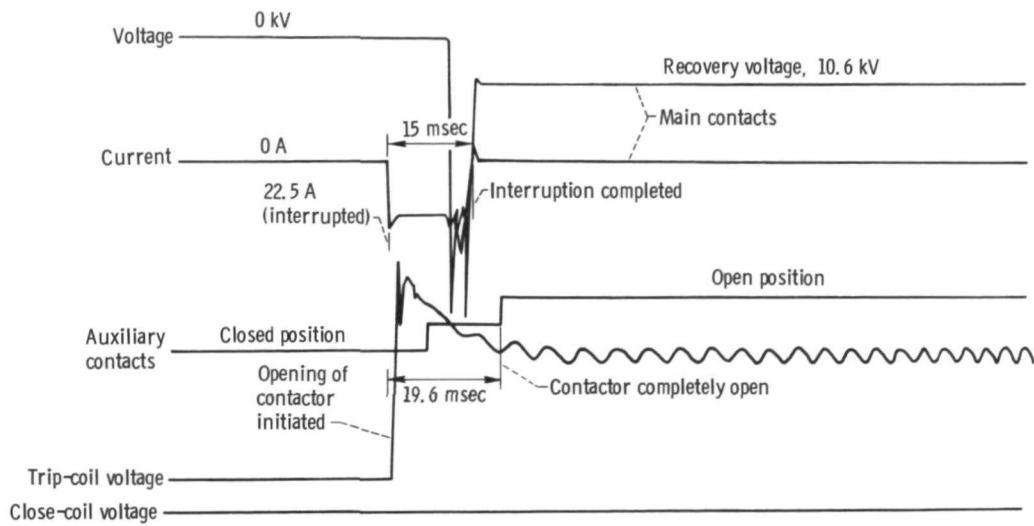


Figure 13. - Visicorder record of direct-current contactor "open only" interruption test with circuit having initial charge of 12.0 kilovolts and recovery voltage of 10.6 kilovolts. Contactor temperature, 540° C (1000° F).

"Conditioning" of the device during the early tests raised the withstand voltage until successful tests could be made with a 10-kilovolt recovery voltage. A copy of the record from a successful "open only" interruption test with a 10.6-kilovolt recovery is shown in figure 13. Interruption took place about 10 milliseconds after the auxiliary contact indicated the contactor mechanism started to move.

A few "close-open" tests were made, and a typical result is shown in figure 14.

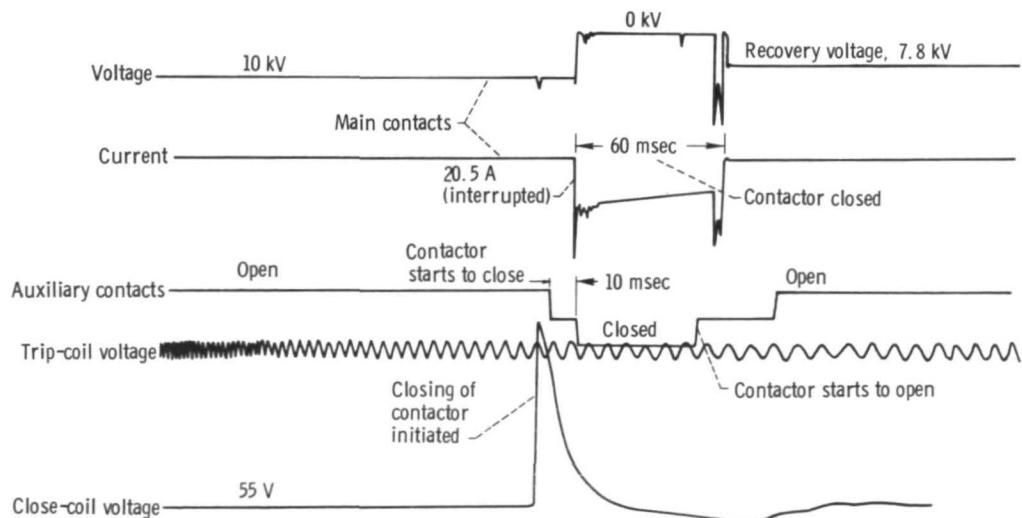


Figure 14. - Visicorder recorder of direct-current contactor "close-open" interruption test with circuit having initial charge of 10.0 kilovolts. Contactor temperature, 540° C (1000° F).

The contacts were closed (and current flowed) for almost 50 milliseconds, resulting in a decrease in the capacitor test bank voltage from 10 kilovolts to 7.8 kilovolts, at which time interruption was accomplished.

No immediate analysis of the actual contact condition after the tests could be made due to their inaccessibility in the capsule; however, the contact resistance (millivolt drop) data indicated that their current-carrying ability increased.

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